Cooperation of Wide Area Control with Renewable Energy Sources for Robust Power Oscillation Damping

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***Abstract*—In this paper, a Wide Area Control (WAC) scheme cooperates with Renewable Energy Sources (RESs) to achieve a robust power oscillation damping. The WAC signals are synthesized by a two-level hierarchical controller which utilizes global measurements from all the installed synchronous generators to maximize the performance of the generators' local controllers. In the proposed WAC scheme, the dynamic operation of RES is also taken into consideration for the implementation of WAC signals, in order to make the generators "aware" of the RES oscillations. Further, the local controller of the RES is modified in order to utilize the available reactive power for compensating any local voltage oscillations, leading that way to a controller which does not require any WAC signals. The performance of the proposed scheme has been tested and validated in the IEEE 9-bus test system where it is indicated that the proposed scheme improves the power system's dynamic stability.**

***Index Terms*— Power system oscillations, Renewable Energy Sources, Wide Area Control, wide area measurements.**

I. INTRODUCTION

Power systems continually increase in size and complexity due to the growing demand, expansion in previously unserved regions, integration of Renewable Energy Sources (RESs), and the interconnection of power systems between different areas. These factors force the power system to operate close to its limits, but more importantly they are responsible for the appearance of oscillations during the power exchange among different areas, which can potentially limit the power transfer capability of the system and can even threaten the stability of the entire power system [1]. Generally, the frequency oscillations of the power system are classified into: i) local (1-2 Hz) or, ii) inter-area oscillations (0.2-1 Hz) depending on whether a generator swings against its system or a number of generators of an area swing against generators of another area [2]. Especially the latter are highly undesirable in the power system and it is important to be compensated effectively.

Wide Area Control (WAC) is the utilization of wide area (global) measurements for the development of suitable control signals in order to overcome the shortcomings of local controllers, dominate the control whenever the system security is threatened, and compensate effectively the inter-area oscillations of the system. The main advantage of the wide area controller compared to local controllers, is the consideration and utilization of wide area measurements, provided by the Phasor Measurement Units (PMUs), improving that way the observability of the control system [3].

Various methodologies have been proposed for the formulation of the WAC signals. In [4] the wide area controller has been designed based on the Takagi-Sugeno fuzzy approach which considers various operating points of the system according to a linear matrix inequality. An adaptive controller based on a lead-lag structure, which uses a measurement driven model is proposed in [5]. In [6], a method for the WAC design is presented based on the utilization of a network control system model according to linear matrix inequality techniques. A controller which does not require any online model of the system and does not need to consider the operating points of the power system in advance, is proposed in [7] and [8]. In [7], the steps for the implementation of a hierarchical controller are presented, which utilizes global signals from all generators in order to formulate WAC signals that improve the local controllers' performances. The study in [8] is based on the same methodology and it presents the modifications that need to be done in the algorithm in order to also include an SVC into the control scheme, along with the generators. All the afore-mentioned methodologies do not consider the effect of the installed RESs on the operation of the power system.

The increasing penetration of RESs in the power grid has made the system even more vulnerable to the appearance of disturbances and can adversely impact the compensation of inter-area oscillations. Therefore, there is a strong need to integrate the RES into the WAC scheme. More specifically, the majority of the published studies utilize doubly-fed induction generator (DFIG) wind farms in the WAC structure, mainly due to the recent addition of the power oscillation damper (POD) on the DFIG wind turbines, which makes possible the coordinate control [9]. In [9] a two-level hierarchical scheme, which exploits centralized and local POD and Power System Stabilizer (PSS) controllers is proposed, to coordinate all DFIG

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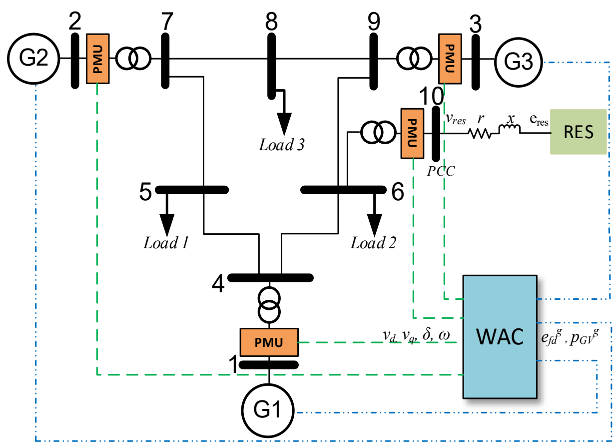

Fig. 1. Proposed cooperation scheme of WAC and RES. Dashed lines represent PMU signals, while dashed-dot lines represent WAC signals.

farms and generators of the system. The authors in [10] present a particle swarm optimization-based wide area damping controller intended for the DFIG wind farms.

In this paper, a two-level hierarchical controller is formulated as shown in Fig. 1, which cooperates with the RES to achieve robust power oscillation damping. The proposed WAC scheme is developed by advancing the methodology described in [7] in order to consider the effect of the RESs. The method of [7] is adopted in this paper, mainly due to its performance, reliability, and flexibility in adding various components of the power system in the WAC structure. In this WAC scheme the dynamic operation of RES is taken into consideration for compensating local and inter-area oscillations. The investigation considers the effect of large scale fully converted RES, the local controller of which has been modified in this paper in order to be able to provide support for damping the voltage oscillations. Therefore, in the proposed structure, the RESs do not need any WAC signals to contribute to the damping of power system oscillations. Electro-Magnetic Transient (EMT) simulations on the IEEE 9-bus test system with integrated large-scale RES are used to validate the performance of the proposed control scheme in compensating local and inter-area oscillations.

II. Wide Area Control Scheme

This section discusses briefly the methodology presented in [7] and the steps of the algorithm to derive the coordinating WAC signals. In addition, the necessary modifications of the methodology are presented here as well, in order to consider the oscillations of the RES when deriving the wide area signals.

A. PMU Measurements

In order to define the WAC signals, global measurements are required from all the generators as shown in Fig. 1 (dashed line). For Wide Area Monitoring and Control (WAMC) applications, PMUs are commonly used to measure voltage and current phasors (magnitude and angle), frequency, and rate of change of frequency. Thus, in this paper the measurement signals are constructed in such a way as to simulate signals provided by PMUs. The measurement signals which are required by the methodology to implement the WAC signals are the generator's terminal voltage (v_t), the frequency (f) and the power angle (δ).

B. Power System Model

In order to obtain the WAC signals, the generator i model is required. Amongst the various models of the synchronous machines, the fourth order model ((1) - (2)), expressed in the local dq-frame, is found adequate for control design. Furthermore, the swing equation (3) is needed as well:

$$T'_{doi}\dot{e}'_{qi} = -e'_{qi} - (x_{di} - x'_{di})i_{di} + E_{fdi} \tag{1}$$

$$T'_{qoi}\dot{e}'_{di} = -e'_{di} + (x_{qi} - x'_{qi})i_{qi} \tag{2}$$

$$\frac{2H_i\omega_{pui}}{\omega_s}\dot{\omega}_i = P_{mi} - (v_{di}I_{di} + v_{qi}I_{qi}) \tag{3}$$

The stator dynamic equations ((4) - (5)) are also necessary, since they connect the generator's terminal voltage with its stator current and its internal voltage:

$$v_{di} = e'_{di} - r_{si}i_{di} + x'_{qi}i_{qi} \tag{4}$$

$$v_{qi} = e'_{qi} - r_{si}i_{qi} - x'_{di}i_{di} \tag{5}$$

where T'_{do} and T'_{qo}, represent the open circuit time constants, x_d and x_q are the synchronous reactances, i_d and i_q are the stator currents and e'_q and e'_d represent the internal voltage, all expressed in the local dq-frame. P_m and ω are the mechanical power and rotor speed, respectively. E_{fd} is the field voltage and ω_s is the synchronous speed of generator i. Lastly, r_s represents the resistance of the generator. All quantities are in per unit.

As expected, for the development of the WAC signals, the local controllers play a vital role. This is due to the fact that the wide area controller aims to provide the right coordination signals to the local controllers, in order to enhance their performance. Therefore, it is important to know the types of the local controllers and furthermore, identify the appropriate local signals, which will be utilized by the WAC to interact with the local controllers. In this study, the exciter DC2A and the general purpose governor were considered in the power system [11]. For the former, the appropriate local signal (which the WAC will interact with) is the excitation signal E_{fd}, while for the latter it is the steam valve outlet P_{GV}.

The governor, in contrast to the exciter (which is directly attached to the generator), connects to the generator through the turbine. Thus, the model of the turbine is needed for deriving the governor's WAC signals. T_{CH} represents the delay due to the steam chest/inlet piping, T_{RH} is the delay of the re-heaters (both delays are in seconds) and F_{HP} is the total turbine power (in per unit) developed in the high-pressure cylinder. For this study the following turbine model has been adopted [11]:

$$P_m = \frac{1}{1+sT_{CH}}\frac{1+sT_{RH}F_{HP}}{1+sT_{RH}}P_{GV} \tag{6}$$

The power network is represented by two current equations. The first one (7) refers to the non-generator buses, while the latter (8) represents the generator buses of the system. G'_{ik} and B'_{ik} are the elements of the admittance matrix:

$$\sum_{k=1}^{m}(G'_{ik} + jB'_{ik})v_k e^{j\theta_k} = 0 \tag{7}$$

$$\frac{-1}{jx'_{di}}(e'_{di}+(x'_{qi}-x'_{di})i_{qi}+je'_{qi})e^{j(\delta_i-\pi/2)}$$
$$+\sum_{k=1}^{m}(G'_{ik}+jB'_{ik})v_k e^{j\theta_k}=0 \tag{8}$$

C. Design of Wide Area Control signals

To derive the WAC signals, essentially a change of variables is performed in order to have as new state variables of the system the terminal voltage of the generators, expressed in the *dq*-frame (v_d and v_q). By performing this change what remains are dynamic equations of the system which depend only on the parameters of the generators. The following steps summarize the methodology:

1) Generator-free bus voltages are expressed in terms of the generators terminal voltages (v_d and v_q).
2) The internal voltage (e_d and e_q) and the stator currents (i_d and i_q) of each generator are expressed in terms of its terminal voltage (v_d and v_q) respectively.
3) The resulted expressions of the internal voltage and stator current are replaced in the model of the generator and swing equation.

The result of applying this methodology are the new dynamic equations of generator *i* terminal voltage as shown in (9) and (10) and of the rotor speed as shown in (11).

$$\dot{v}_{di}=a_{1i}v_{di}+a_{2i}v_{qi}+p_{1i}E_{fdi}+\psi_{di} \tag{9}$$
$$\dot{v}_{qi}=b_{1i}v_{di}+b_{2i}v_{qi}+p_{2i}E_{fdi}+\psi_{qi} \tag{10}$$
$$\frac{2H_i\omega_{pui}}{\omega_s}\dot{\omega}_i=P_{mi}-G_{ii}^{f}(v_{di}^2+v_{qi}^2)-\psi_{\omega i} \tag{11}$$

The a_1, a_2, b_1, b_2, p_1 and p_2 are parameters based on the network topology resulting from the application of the methodology. ψ_d, ψ_q, ψ_ω are the perturbation terms from other generators on generator *i*.

The new dynamic equations are then used to derive the WAC signals. This is done by replacing v_d, v_q and ω, in the dynamic equations, by their error compared to their steady state values (de_d, de_q and de_ω). The resulting expressions are then differentiated until the local controllers' inputs appear in the equations. By doing this and by decomposing each control input of the local controllers, into local and global, the WAC signals are determined by selecting the global control inputs in such a way so that they will cancel out all the interactions of all the other generators to generator *i* [7]. The following set of equations shows the resulted WAC signals for the exciter and governor, respectively.

$$e_{fdi}^{g}=\frac{-(\psi_{de_d}^{i}de_{di}+\psi_{de_q}^{i}de_{qi})}{p_{1i}de_{di}+p_{2i}de_{qi}} \tag{12}$$
$$p_{GVi}^{g}=-\frac{T_{CH}\dot{\psi}_{\omega}^{g}+\psi_{\omega}^{g}}{F_{HP}} \tag{13}$$

D. Consideration of RES in the WAC scheme

The key point of this section is to realize that the benefit of utilizing WAC signals (for cancelling out the interactions amongst generators) is that the performance of the local controllers can be maximized and the damping of the power system oscillations is properly coordinated. One of the main contributions of this paper is the inclusion of all the interactions amongst generators and RES in the formulation of the WAC signals. The benefit of doing this, is that the generators become "aware" of the RES oscillations through the WAC signals and further, the RES will be able to contribute for damping out any local oscillations (as will be suggested in Section III), increasing that way the damping capability of the entire system (instead of decreasing it) under high penetration of RES.

To achieve this, firstly measurement signals similar to the ones collected from the generators, must be obtained from the RES as well. For this reason, a PMU is added at the Point of Common Coupling (PCC) of the renewable, in order to provide the RES terminal voltage phasor (v_{res}) and the frequency (*f*). In addition, the power angle is also required when applying the methodology. The problem in this case is that, in contrast to the generators, the RESs do not have a power angle. To overcome this obstacle and make the methodology applicable for renewables, a virtual power angle (δ_{res}) for RES is introduced that represents the angle between the v_{res} and the virtual e_{res}. The latter depicts the fundamental voltage phasor at the output of the grid tied inverter (before the filter) as shown in Fig. 1. The δ_{res} can be calculated based on v_{res} and the injected current phasor (i_{res}). By transforming these phasors into the *dq*-frame, the corresponding v_{res-d} and v_{res-q}, and the i_{res-d} and i_{res-q} are derived. Hence, (14) and (15) can be used for calculating the corresponding e_{res-d} and e_{res-q} and as a result the virtual δ_{res} can be obtained by (16).

$$e_{res-d}=v_{res-d}+ri_{res-d}-xi_{res-q} \tag{14}$$
$$e_{res-q}=v_{res-q}+ri_{res-q}+xi_{res-d} \tag{15}$$
$$\delta_{res}=\arctan\left(\frac{e_{res-d}}{e_{res-q}}\right) \tag{16}$$

It is to be noted that *r* and *x* represent the in series resistance and reactance of the filter between the inverter and the PCC (Fig. 1).

The next step is to consider RES buses as "generator buses" while applying the first step of the methodology described previously. By doing so, the remaining buses are expressed in terms of the generators and RES terminal voltages. The following steps remain as they are, considering only the generators.

The proposed modification of the methodology results to a structure where the controller is considering the oscillations of the RES, when deriving the required WAC signals for the generators, through the perturbation terms. The advantage is that the RES controller does not require any WAC signals. Based on this method, the wide area controller is now able to cooperate with the renewable system for effective damping of the power system oscillations. The following section describes the necessary modifications of the RES local controller in order to be able to compensate any local oscillations.

III. RES WITH LOCAL VOLTAGE SUPPORT SCHEME

This study presents a WAC scheme which considers the operation of both generators and renewables for damping the power system oscillations. The WAC signals are send only to

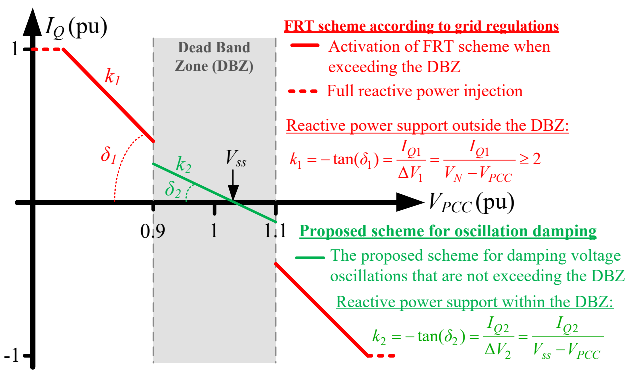

Fig. 2. Reactive support scheme of RES. With red color, the current grid regulatios are depicted and with green color, the proposed scheme for enabling RES to contribute into the oscillation damping is presented.

the generators in order to compensate the oscillations caused by a disturbance in the system. Therefore, RESs are not regulated in a centralized way through the WAC scheme.

In order to enable the renewable to locally contribute to the voltage oscillation damping, some modifications are proposed in this paper on the reactive control strategies of RES. According to the current regulations for interconnecting RES [12], the reactive or Fault Ride Through (FRT) support by RES is only activated when the voltage at the PCC is violating the limits of the Dead Band Zone (DBZ), defined as ±10% variation around the nominal voltage (V_N), as shown Fig. 2. The grid regulations [12], define the reactive current (I_{Q1}) that should be injected by the RES as given by,

$$I_{Q1} = k_1 \cdot \Delta V_1 = k_1 \cdot (V_N - V_{PCC}), \tag{17}$$

where V_N=1 pu and V_{PCC} the voltage at the PCC. The parameter k_1 should be equal or greater than two, according to [12], in order to provide an aggressive voltage support under intense voltage sag.

However, in most cases, disturbances on the power system cause inter-area oscillations that may not be observed as voltage limits violations. For example, an expected voltage oscillation with maximum overshoot of 0.05 pu (and a slow oscillation frequency of 0.5-1 Hz due to the large inertia of the generators) and with an extended duration (5-10 s) will not activate the reactive support of RES. Hence, the renewable cannot support the grid for damping such oscillations.

A reactive support scheme is proposed here in order to enable the local contribution of RES for damping power system oscillations. The proposed scheme can be applied on the grid tied inverter of the renewable in order to regulate the reactive support in the presence of such inter-area oscillations where the voltage oscillates but without exceeding the DBZ. The proposed scheme defines the reactive support by the RES when a voltage oscillation occurs (that does not violate the DBZ), as shown in Fig. 2. The required reactive current (I_{Q2}) is given by,

$$I_{Q2} = k_2 \cdot \Delta V_2 = k_2 \cdot (V_{SS} - V_{PCC}), \tag{18}$$

where k_2 is a parameter that determines how intense is the reactive support during inter-area oscillations and should be less than two (small voltage oscillations). For the purposes of this paper, k_2 is set to one. Further, V_{ss} represents the steady state voltage of the RES at the PCC prior the inter-area oscillation and can be calculated according to the first order low-pass filter of (19).

$$V_{SS} = \frac{\omega_f}{s + \omega_f} V_{PCC}, \tag{19}$$

The cutoff frequency of the frequency (ω_f) of the filter is set to 2π0.05 rad/s in order not to be affected by the inter-area oscillations with a frequency of 0.5-1 Hz.

Therefore, the proposed scheme for reactive support introduce a virtual voltage inertia on the RES that resists to small changes of the voltage at the PCC by injecting or absorbing reactive power. The proposed scheme can locally enable the renewable to contribute to the compensation of the inter-area oscillations and can smoothly cooperate with the proposed WAC scheme of Section II.

IV. Demonstration of Concept

The proposed WAC and RES coordination has been implemented and applied to the IEEE 9-bus test system [13], which consists of 3 machines and 3 loads as shown in Fig. 1. It is to be noted that the initial total load of the system is 315 MW and 115 MVAr. Each generator is equipped with its own local controllers (exciter and governor) in order to achieve a dynamic response. The 20 MVA RES is integrated at bus 6 of the system through a step-up transformer. In the examined case studies, if not stated otherwise, the output of the renewable is set at 10 MW while constant wind conditions are assumed. The RES is developed based on a full detailed model of a central grid tied inverter [12] (a typical three-phase two-level voltage source converter based on six switching IGBTs). The controller of the renewable is based on advanced synchronization and current control techniques ([14], [15]) in order to achieve a proper operation under grid disturbances. All the local controllers (of RES and generators) have been digitally designed in discrete time (using a sampling rate of 10 kHz). The construction of the test system, wide area controller and RES is done using EMT simulations in MATLAB/Simulink. Furthermore, it is worth mentioning that the RES location affects the WAC performance, however very similar results were observed when the renewable was tested at buses 5, 6 and 8.

The performance and robustness of the proposed WAC-RES scheme is verified by various simulation case studies. This includes load change, symmetric and asymmetric grid faults, based on the IEEE 9-bus test system. For the load change case study, a 50% increase of Load 2 (by 45 MW and 15 MVAr) takes place (which represents 14% increase of the initial total load). The symmetric fault case study considers a 5-cycle three-phase fault (grounded), while for the asymmetric fault case study, a 5-cycle single-phase ground fault takes place. Both types of faults occur in the middle of the line connecting bus 9 with bus 6. All the disturbances take place at t=8 s.

The objective of this section is to compare the performance of the proposed WAC scheme that cooperates with the RES (WAC-RES) versus the normal operation scenario where no WAC exists in the system (No WAC) and the scenario where WAC exists in the system but it does not cooperate with the RES (WAC only). The results of Fig. 3 and Fig. 4 provide the generator G2 terminal voltage and generator G3 rotor speed of

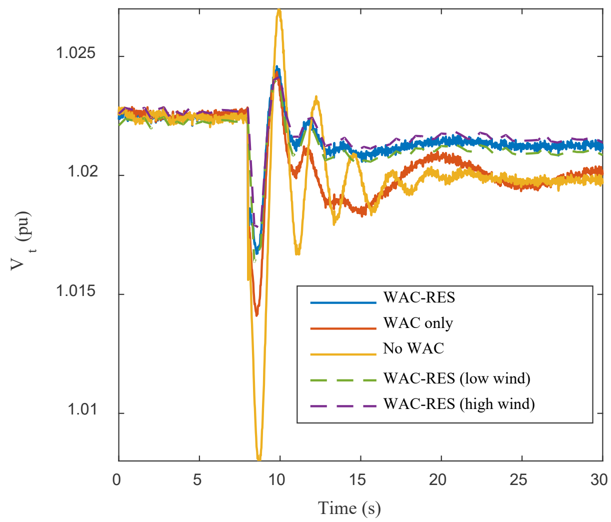

Fig. 3. Terminal voltage oscillation of generator G2, during load change.

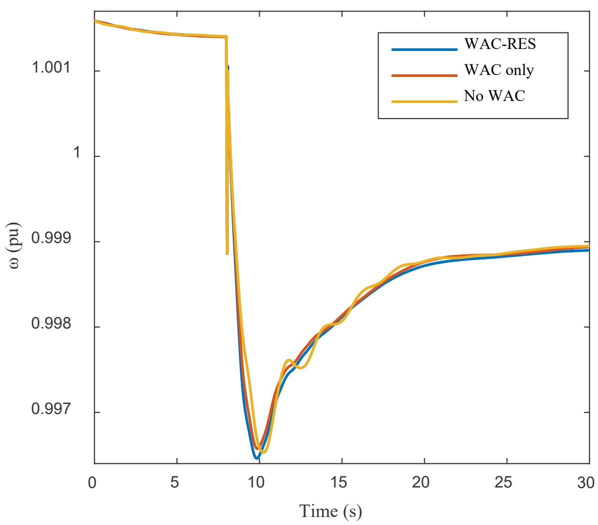

Fig. 4. Rotor speed oscillation of generator G3, during load change.

all three scenarios at the event of a load change. It is worth to mention that in this case study the impact of the proposed WAC scheme is more evident. More specifically, the maximum voltage overshoot of the oscillation (Fig. 3) is 1.45% on the No WAC scenario, 0.85% on the WAC only scenario and 0.55% on the proposed WAC-RES scenario. Further, the duration of the oscillations in the case of the proposed WAC-RES scenario is approximately half compared to the duration of the rest scenarios. For the rotor speed (Fig. 4), it can be noted that the proposed WAC-RES scenario, provides additional damping to the rotor speed oscillation compared to the WAC only and No WAC scenarios. Additionally, in this case study, the impact of the high and low wind conditions on the WAC-RES scheme is also investigated. It is noted that in high wind conditions, the RES produces 15 MW, while in low wind conditions it produces only 5 MW. The results for different wind scenarios are presented in Fig. 3 as well. Here it can be observed that the wind speed variations have a small effect on the performance of the WAC-RES scheme.

Fig. 5 and Fig. 6 depict the simulation results for a 5-cycle symmetric short circuit fault. More specifically, Fig. 5 shows the terminal voltage of G2, where it can be seen that the performance of the proposed method is considerably better than the No WAC scenario and furthermore one can note that it provides improved damping of the power system oscillations, compared to the WAC only scenario. The behavior of the rotor speed of G1 is illustrated in Fig. 6, where it reveals that in this case study, the damping capability of the proposed WAC-RES is comparable with the response of the WAC only scenario, but still considerably better than the No WAC scenario.

Lastly, for the asymmetric fault case study, Fig. 7 and Fig. 8 present the results for the G1 terminal voltage and G2 rotor speed respectively, at the event of a 5-cycle single-phase ground fault. Both figures point out that the proposed WAC-RES scenario provides additional damping compared to the WAC only scenario, even at the event of an asymmetric fault. Furthermore, it is evident that the proposed WAC-RES scenario has significantly better response than the No WAC scenario.

Overall, it is clear that the performance of the proposed method is considerably better than the normal operation scenario. It is also important to note that the proposed method provides even better damping of the power system oscillations,

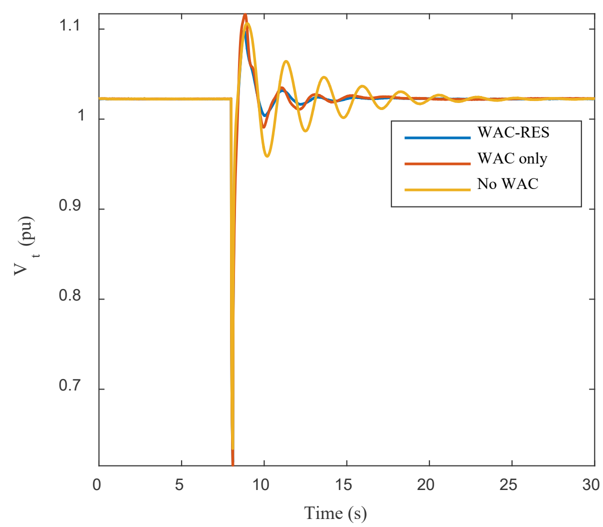

Fig. 5. Terminal voltage oscillation of generator G2, during symmetric fault

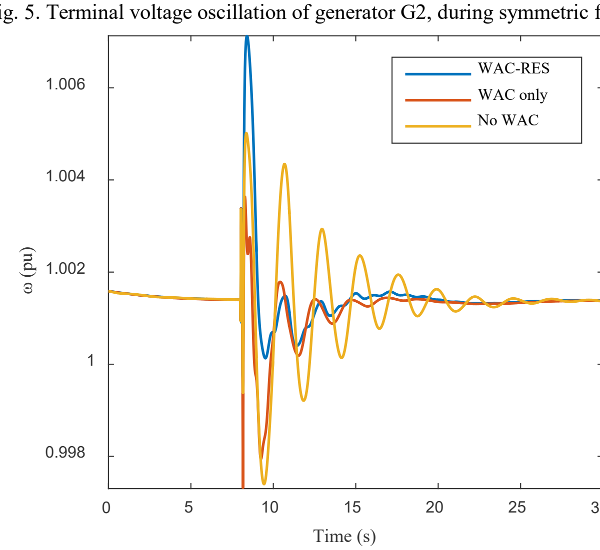

Fig. 6. Rotor speed oscillation of generator G1, during symmetric fault.

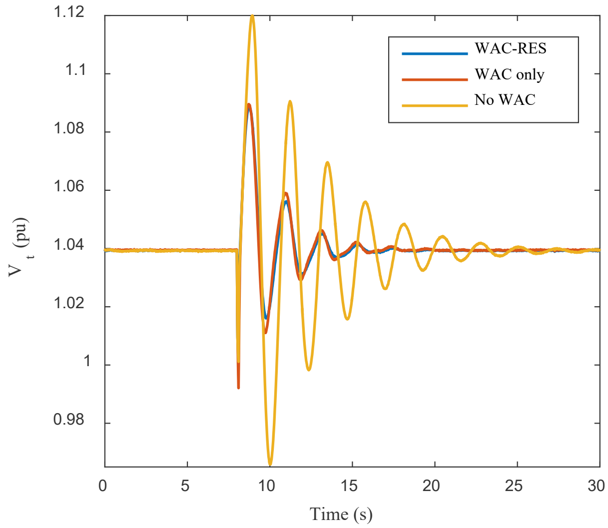

Fig. 7.Terminal voltage oscillation of generator G1, during asymmetric fault.

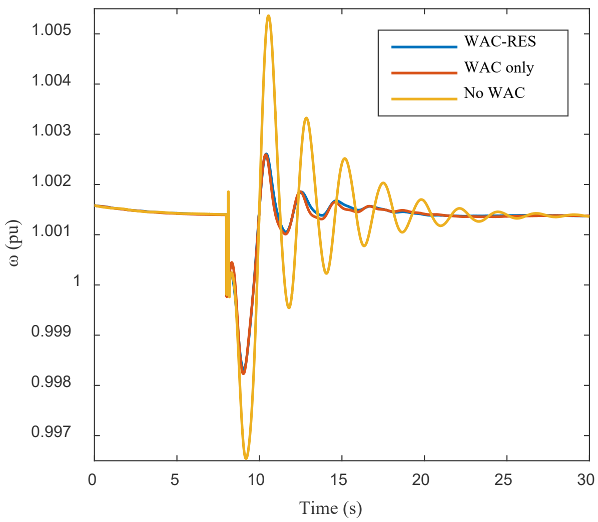

Fig. 8. Rotor speed oscillation of generator G2, during asymmetric fault.

than when the wide area controller operates on its own without considering the effect of the renewable.

V. Conclusion

A cooperation architecture between a hierarchical WAC scheme and a renewable system is proposed to improve the dynamic stability of power systems. This cooperation scheme became feasible by making the generators "aware" of the RES oscillations through the WAC signals. In addition, the damping capability of the system is increased by modifying the RES local controller to properly utilize the available reactive power of the renewable in order to damp out any local oscillations. The advantage of this control scheme, is that there is no need to derive WAC signals for the control of RESs and therefore their integration into the WAC scheme is not required to improve the dynamic stability of the system. The performance of the proposed method is evaluated by case studies based on the IEEE 9-bus test system, where various disturbances were investigated, such as load increase, symmetric and asymmetric grid faults. The simulation results indicate that the power system oscillations are effectively compensated by utilizing the proposed cooperation scheme. The results are obtained in comparison with the normal operation scenario where no WAC exists in the system and the scenario where there is no cooperation between WAC and RES, in order to present the improved damping performance of the proposed scheme.

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